THE INTERNATIONAL SYMPOSIUM ON GRAVITATIONAL COLLAPSE

HONG-YEE CHIU[*] (Columbia U.)

NASA. Goddard Institute for Space Studies,

New York, New York

and

Columbia University

New York, New York

Symp. held at Dallas; 16-18 Dec. 1963

Submitted for Publication

Fellow, Academia Sinica, Republic of China

The International Symposium on Gravitational Collapse

The central theme of the discussions held at the International
Symposium on Gravitational Collapse* was a certain class of
cosmic radio sources discovered and optically identified during the
past few years through the efforts of a number of astronomers
and astrophysicists. At the meeting, attended by more than 300
astronomers and physicists, certain possible theoretical inter-
pretations were presented.

Most cosmic radio sources are "radio galaxies" with the
exception of a few supernova remnants which are in our galaxy.
Although flare stars do emit radio waves occasionally, no ordinary
stars with strong, steady radio emission have been found. The
typical optical power of stars is from 10^{30} ergs/sec (white dwarfs)
to 10^{38} ergs/sec (super giants). For comparison, the optical
power of the sun is 4×10^{33} ergs/sec. The typical radio power of
supernova remnants is around 10^{36} ergs/sec. For a giant galaxy
(containing approximately 10^{11}-10^{12} stars with a total mass of
around 10^{11} $\odot$, where $\odot$ = solar mass = 2×10^{23} g) the optical
power is around 10^{44} ergs/sec. Radio emission from normal galaxies is
generally weaker, the power ranging from 10^{37}-10^{39} ergs/sec.

For certain peculiar galaxies, the so-called "radio galaxies," the radio emission rate ranges from 10^{41}-$10^{44.5}$ ergs/sec.

However, since 1960, another kind of strange object has been found - "quasi-stellar radio sources," these formed the center of discussion at the symposium. Their radio power is around 10^{44}ergs/sec and their optical power is around 10^{46} ergs/sec, which is 100 times the total energy ouput rate of a giant galaxy! To date 9 of these objects have been found. On photographic plates these peculiar radio sources have star-like appearances and one of them showed erratic light variations with a time constant of the order of one year and a long term quasi-period of 10 years. A modest estimate of the total energy content of each of these objects (in the form of the kinetic energy of electrons of 1 Bev energy) gives a minimum of 10^{60} ergs, which is the rest energy of about 10^6 suns.

Are "quasi-stellar radio sources" stars? Ordinary stellar structure theory precludes stars of mass greater than 100⊙. In such stars, radiation pressure dominates and because of the thermo-dynamic properties of radiation, these stars will pulsate with large amplitudes. As a result of this pulsation, mass will be ejected thereby reducing the mass of the star. Are "quasi-stellar radio sources" galaxies? Their angular size is less than 0.5", while normal galaxies at corresponding distances (determined by their red shift) will have an angular size of the order of 3". In several cases, the light variation precludes this possibility because galaxies do not have light variations.

So far, the clumsily long name "quasi-stellar radio sources" is used to describe these objects. Because the nature of these objects is entirely unknown, it is hard to prepare a short, appropriate nomenclature for them so that their essential properties are obvious from their name. For convenience, the abbreviated form "quasar" will be used throughout this paper.

The idea of having a meeting on gravitational collapse came after the discoveries of the enormous energy output of quasars and the subsequent gravitational collapse theory of F. Hoyle of Cambridge University and W. A. Fowler of Cal. Tech. to explain this enormous energy output. When the symposium met, the original hypothesis of F. Hoyle and W.A. Fowler (reviewed by E. M. Burbidge of University of California at La Jolla) was abandoned, and replaced by those to be reported later. Meanwhile, new observational data had been accumulated and was presented at the meeting. At the present time, it is the author's opinion that the interior structure and the physical mechanism of the energy production of quasars are still not understood.

Fusion of hydrogen into heavier elements will yield an energy of about 1% of the rest energy of matter. If the energy source of the quasars were nuclear in nature, it would be necessary that $10^8 \odot$ of hydrogen be burned in around 10^6 years. It is rather unlikely that nuclear energy could be released in unison on such a large scale. Moreover, nuclear reactions usually take place in the

interior of a star, the energy released gradually diffuses out

and finally is radiated thermally as black body radiation peaked

at an energy of around 2 ev. How can the energy of electrons be

elevated from a few ev to a few Bev without violating the second

law of thermodynamics? Using the most efficient thermodynamic

cycle, a nuclear energy source many orders of magnitude higher

is needed. Therefore there is only one energy source left for us

to consider: gravitational energy. Incidentally, the gravitational

field is the weakest field in nature, but it is the only one that
allows us (at least theoretically) to extract up to 8/9 of the rest
energy of matter.

After this brief introduction to the central theme of the

discussions, I shall now report the individual papers that were

presented at the symposium. In order to have continuity in this

report, I shall not report the talks chronologically, but in a

logical manner.

Reviewing the common properties of radio sources, T. Matthews

of Cal. Tech. pointed out that radio emission from normal galaxies

[Fig. 1] is rather weak compared with their optical emission. Their radio

power is around 10^{37-39} ergs/sec while their optical power is

around 10^{44} ergs/sec. Some rare, peculiar spiral galaxies may

have a radio emissive power of around 10^{40} ergs/sec. Strong radio

galaxies with a radio power of 10^{41-44} ergs/sec are most frequently

found among the so-called D systems. These are galaxies with an

excessively bright nucleus (Seyfert galaxy). Some strong sources

are also identified with elliptical galaxies. The optical emission rate of quasars is around 10^{46} ergs/sec and their radio emssion rate is around 10^{44} ergs/sec.

To date, a total number of 9 quasars have been identified from the contents of the revised 3C catalogue (3C stands for the Third Cambridge Catalogue of Radio Sources) which contains about 470 radio sources,

many of them are still unidentified optically. This catalogue was compiled by a group working under M. Ryle of the University of Cambridge. The two quasars which have been extensively studied and which were extensively discussed at the meeting have catalogure numbers 3C273 and 3C48 respectively.

Radio interferometers with a resolution of the order of 1" of arc were first used to study the shape of some of the stronger quasars. This method also enables one to locate accurate positions for these sources. This was done chiefly by the Manchester group (R.P. Allen, B. Anderson, R. G. Conway, H. P. Palmer, V. C. Reddish, and B. Rowson) and by the Cal. Tech. group (P. Maltby, T. A. Matthews, and A. T. Moffet). In the radio position of 3C48, an object resembling a 16^m star was found on the photographic plates.* This

[Fig. 2] "star" was surrounded by a nebula measuring 5" x 12" which does not resemble any galaxy.

At the same time, lunar occultation observations of 3C273 were carried out by the Australian group (C. Hazard, M. B. Mackey,

---

*^{m}stands for the magnitude. $m = -2.5 \log_{10} F + C$ where F is the observed energy flux and C is a constant. At a distance of 32.5 light years the sun has a magnitude of + 4.85. A 6^m star is just barely visible to the eye. A difference of 5 magnitudes amounts to a difference in measured energy flux of 100.

and A. J. Shimmins). This other method of observation provided

an optical identification for 3C273. Because of gravitational

perturbations, the orbital plane of the moon is not fixed in

space but precesses with a period of around 19 years. Thus, the

moon with an angular size of 30 minutes of arc can occult

stars within a belt of 20° as it moves around the earth. When

a radio source is occulted, one can learn from the diffraction

[Fig. 3] pattern about the location, shape and size of the radio source.

Figure 3 shows some observed diffraction patterns of 3C273. In

particular, it is easy to tell if a source is an extended one. It

was found that 3C273 consists of two sources, A and B, their separa-

tion is 19.5". Component B is slightly elliptical and 4 times

[Fig. 4] weaker than component A. Using the 200" Hale telescope, A. Sandage

of Mt. Wilson and Palomar/ Observatory obtained photographs which show, at

the radio position of A, a nebula shaped as a jet, pointing away

[Fig. 5] from a 13^{m} star-like object which is identified as component B.

Radio spectra for both components of 3C273 and for 3C48

have been obtained. Before we go on, we shall briefly describe

the mechanism for radio emission and the nature of radio spectra.

The optical radiation of stars and nebulae are chiefly emitted by

thermally excited ions. The spectra of stars and nebulae are rich

in absorption or emission lines, their overall features can be

understood in terms of black body radiation peaked around certain

optical wavelengths. The radio spectra that is normally observed

can be broadly classified into two categories: thermal and synchro-

tron emission. In the thermal spectrum, the intensity per unit freqency increases towards shorter wavelengths for emission from "optically thick" emitters. This kind of spectrum resembles that of the long wavelength end of a black body thermal radiation, hence its name. Most likely it is produced by free-free transitions of the electrons in the Coulomb field of ions (bremsstrahlung). In the synchrotron spectrum, the intensity decreases towards the shorter wavelengths, and usually the intensity per unit frequency is proportional to ν^{-m} where ν is the frequency and m is a positive number usually between 0.3 and 1.2; and for most sources m has a value of around 0.8.

The orbits of electrons in a magnetic field are not straight lines but curves. Hence these electrons suffer acceleration while travelling on a curved path. These "accelerated" electrons then radiate polarized electromagnetic waves primarily in the radio region. Such radiation from monoenergetic electrons was first observed in electron synchrotrons, hence the name synchrotron radiation. The observed cosmic ray spectrum is usually

$$N(E)dE = E^{-k}dE$$

where $N(E)dE$ is the flux in the energy band dE and k is a positive number, k = 1.5 for high energy cosmic ray particles. We may assume that the relativistic electron component of cosmic rays also obeys this law, then the synchrotron radiation intensity per unit frequency is proportional to ν^{-m}.

[Fig. 6]

The radio spectrum of 3C273 is shown in Figure 6. It is a composite of the two sources A and B, and can be resolved as indicated. This resolution was obtained from lunar occultation observations. The spectrum of A seems to belong to the synchrotron type, and that of B to the thermal type. However, this interpretation of the observed spectrum of source B would require a temperature of the order of 10^9 °K. Such a high temperature contradicts the lifetime estimated by present theory.

The optical spectrum of 3C48 has also been available for some time. Several emission lines were found, but no unequivocal identification with lines of known atoms or ions could be made. Moreover, J. Greenstein of Cal. Tech. found that the spectra of some fainter quasars, 3C147, 3C196, and 3C286 (also showing somewhat weaker emission lines) looked quite different from that of 3C48.

M. Schmidt studied the spectrum of the bright object, 3C273. He found four emission lines which formed a simple harmonic pattern with separation and intensity decreasing towards the ultra-violet. This series of lines looks like that of any hydrogen-like atoms. Unfortunately, they correspond to no elements found on earth. A unique interpretation can only be made by assuming a red shift $(\Delta\lambda/\lambda)$ of 0.16 and that the emitting element is hydrogen. A far bigger red shift has to be assumed if the emitting element consists of other hydrogen-like atoms. Indeed, with this interpretation, a red-shifted Hα line (shifted from 6563Å to 7590Å) was found in the

infrared by J. B. Oke of Cal Tech. Similarily, the line spectra of
all other quasars can be interpreted as red-shifted emission lines
and forbidden lines. In 3C48 the emission line identified corre-
sponds to that of [MgII] and the forbidden lines to those of [O II],
[Ne III] and [Ne IV]. In 3C48 the red shift is 0.37. The corre-
sponding velocity (if the red shift is interpreted as the Doppler
shift) is around 0.15 c and 0.3 c for 3C273 and 3C48 respectively.*

[Fig. 7] Figure 7 shows the red shift interpretation of a number of quasars.

Another feature of quasars is that they show a strong ultra-
violet excess even at a red shift of $\frac{\Delta\lambda}{\lambda} = 0.8$. Using filter
techniques, A.R. Sandage and M. Ryle have successfully identified
a few more quasars (3C9, 3C216, 3C245) from a number of objects
showing strong ultra-violet excess.

Could quasars be stars in our galaxy with a high receding
velocity? This is extremely unlikely. First, the gravitational
field of our galaxy cannot retain stars with a velocity $> 10^{-3}$ c.
Second, the proper motion (apparent motion of stars with respect
to background stars) should be large.

W. H. Jefferys of Wesleyan University (Connecticut) studied
the proper motion of 3C273. Since 3C273 is fairly bright, its image was
found among many sky patrol plates dating back to 1888. Plates from many

---

*The Doppler shift is $\frac{d\nu}{\nu} = -\frac{v}{c}\Big/\sqrt{1- \frac{v^2}{c^2}}$, where v is the relative
velocity of the source and the observer. For the same velocity
most cosmological theories predict a shift $\frac{d\nu}{\nu}$ in between $-\frac{v}{c}\Big/\sqrt{1- \frac{v^2}{c^2}}$
and $-\frac{v}{c}$ (linear).

observatories using different telescopes, accumulated over the past 50 years, were used to determine the proper motion. The inertial system used is the so-called FK3 system. This refers to a group of stars catalogued in the Dritter (Third) Fundamental-Katalog des Berliner Astronomischen Jahebuchs (Kopff, 1934). In this catalogue, about 924 stars are listed with the highest precision then available.[*] The measured proper motion of 3C273 is 0.001 ± 0.0025 seconds of arc per year. The standard deviation is from uncertainties associated with the accuracy of the absolute position of stars in the FK3 system. From the value of proper motion and the velocity derived from the differential rotation of our galaxy, the distance of 3C273 is > 65,000 light years, and this puts 3C273 on the border of our galaxy (the size of our galaxy is 10^5 light years). A similar result was also obtained by W. J. Luyten of University of Minnesota using more recent plates.

Can the red shift be gravitational in nature? The red shift of light from a self-gravitating body of radius R, mass M, is of the order of $\frac{GM}{Rc^2} = 10^{-6} \frac{(M/\odot)}{(R/R_\odot)}$. ($R_\odot$ = solar radius = 7×10^{10} cm). In order to have a red shift as large as 0.1, $\frac{(M/\odot)}{(R/R_\odot)} \approx 10^5$. For a star of one solar mass, a R ~ 10^6 cm, and a density of about 10^{15} g/cm^3 would be required. (E. E. Salpeter of Cornell Univeristy reviewed the equilibrium configuration of superdense stars. It is not possible for superdense stars of mass >> $\odot$ to exist and also the red shift of light from superdense stars cannot exceed 0.3.) The presence of spectral lines implies a surface temperature of the

---

[*]Recently the FK4 Catalogue, containing more than 1200 stars, has been published.

order 10^4 °K. From the radius of superdense stars, one can
estimate the total radiative power, and thus deduce the distance
from the observed flux.

If 3C273 were a superdense star, its distance would be 0.3 light
years and it would be practically inside our solar system! From
the intensity of the forbidden lines J. Greenstein/concluded that
further
the distance would be even smaller. Such stars would have been
discovered by Kepler through the failure of Kepler's laws!

One may also assume that quasars have bigger masses and
bigger radii than superdense stars. For example, one can assume
that 3C273 is a star at a distance of 1000 light years. In order
to be compatible with the energy output rate, the radius has to
be 10^{13} cm. Then, in order to account for the red shift, the mass
has to be 10^7 ⊙! W. A. Fowler pointed out that such stars cannot
even burn hydrogen, because they would fall within their gravi-
tational radius before the temperature would be high enough to
burn hydrogen (it requires a temperature of 10^7 °K to burn hydrogen)!
California at Berkeley
D. Williams of University of/reported the observation of inter-
stellar absorption lines in 3C273. When radio waves of distant
galaxies reach us, part of the energy at 21 cm wavelength is absorbed
by hydrogen in our galaxy. A very weak 21 cm absorption line was
found in the radio spectrum of 3C273 with a velocity of 1 Km ± 10 km.
This effect, however, is very marginal.

Since no other rational interpretation can be given to the
red shift, one can only attribute the red shift to cosmological

red shift. Using Hubble's law, the distance of 3C273 is placed
at 1.8×10^9 light years. This gives an energy output rate for
3C273 of 10^{46} ergs/sec at optical frequency. Many people will
question if Hubble's law is well established. Hubble's law
states that the distance of galaxies to us is linearly related
to their red shift:

$$\text{Distance} = \frac{\text{Recession velocity}}{H}$$

The proportionality constant H ($\approx \frac{100 \text{ Km}}{\text{sec-Mega Parsec}}$) is known as
Hubble's constant. $H^{-1}c$ is a measure for the dimension of our
universe; at a distance $\approx H^{-1}c$ the red shift is infinite. One
often hears that astronomical observations are not accurate
enough to distinguish one type of cosmological theory from ano-
ther, and many have expressed doubts about applying Hubble's
law to obtain the distances of unknown objects from their red
shift. The answer is that these two problems are somewhat
different in nature. Assuming that the local density of galaxies
is the same throughout the universe <u>at a given time</u> and that the
curvature of the universe is everywhere constant, different cos-
mological theories will predict different galactic densities as a
function of the distance (this galactic density is observed from a single space-
time point) and the distance is obtained from the red shift from
the above equation. That the galactic density would be observed
at a single space-time point is different for different cosmological
theories is because of the expansion of the universe and that the

expanding rate as a function of the distance is different in different theories. Unfortunately, different cosmological theories predict measurable differences in galactic densities only at distances much beyond the reach of the world's most powerful telescope - the 200" Hale telescope at Mt. Palomar. Hubble's law, however, is established accurately for neighboring galaxies by applying knowledge of the period-luminosity relation of Cepheid variables. (Cepheids are bright variables of luminosity $\sim 10^5$ $L_\odot$ and their period is related to their luminosity by some simple law. Hence, by observing the period and the apparent brightness of Cepheid variables of other galaxies one can obtain a distance.) Then the absolute brightness of more distant galaxies is related to the red shift through a complicated statistical analysis eliminating the difference in intrinsic luminosities of individual galaxies. The result is a law that can be trusted to within a factor of 2 in distance estimates. Hence we believe that Hubble's law may be applied to quasars to obtain their distance accurately.

H. J. Smith of McDonald Observatory took a bold look at quasars. Is there light variation in these objects? Sky patrol plates from Harvard University Observatory are available back to 1888. Although a large number of old plates have aged and become unreliable, some of them are still in fairly good condition. In measuring light variations, one only needs to compare the image of 3C273 witn neighboring stars. H. J. Smith and D. Hoffleit of

Yale found a large light variation with an amplitude up to 50 %

[Fig. 8] and a quasi-cycle of 15 years. A. $\overset{R.}{\underset{\wedge}{\text{Sandage}}}$ observed 3C273,

13C48, and 3C196 more recently with a photoelectric device and

found some erratic variations up to a few tenths of a magnitude.

If 3C273 were a galaxy with a nominal number of stars ($\sim 10^{10}$),

from statistical theory, the expected annual variation would be

much less than 10^{-5} of the variation of any star. This limit is

obtained by assuming that all stars in the galaxy are variables

of the same period. Hence it is not possible that 3C273 and other

quasars are compact galaxies. Further, in order that the light

from such an object can vary with a time constant $\sim$ 1 year (the

shortest variation observed), the physical dimension of 3C273 cannot

be much bigger than the time it takes light to go across it, namely

one light year.

Having established that qusars are not local stars nor galaxies,

the next thing to do was to further study the details of their spectra.

J. Greenstein reported that these lines have been identified with

the forbidden lines 0^+, Ne^{++}, and Ne^{++++}. Certain atomic excited

states decay through higher order interactions, and their lifetime

is long ($\sim$ 1 second). Under ordinary laboratory discharge tube

density ($\gtrsim 10^{15}$ particles/cm^3), collisional de-excitation takes

place before atoms in these excited states can decay, and the corres-

ponding lines are ordinarily unobservable in the laboratory (for-

bidden). The presence of forbidden lines indicates low electron

density ($< 10^7/cm^3$). As the density increases, forbidden lines

gradually disappear.

The observed forbidden lines are [O II], [O III], [Ne III] ([Mg II]

is not a forbidden line.) From their observed relative strength the

electron number density may be established. Knowing the distance

from the red shift, the absolute intensity of the strength of these

lines and hence the total number of atoms emitting them may be

determined. Table I lists J. Greenstein's results.

Table I

Quasar	N_e/cm^3	Radius (parsec)	M/⊙ (of emitting parts)
3C273	10^7	0.6	2×10^5
3C48	10^5	5	2×10^6

If quasars were superdense stars, the differential red shift

at different layers would limit the thickness of the emitting layer

to that corresponding to the observed width of forbidden lines.

This would limit the total number of emitting ions. From this
                                                    concluded that
limit and the observed intensity of forbidden lines J. Greenstein/
            would have
quasars /   to be as close as the moon! Such large gravitational

perturbations on the solar system could not have escaped the keen

eye of Kepler. Hence, from the presence of forbidden lines one can

argue indirectly but strongly that the red shift cannot be gravita-

tional.

The lower limit for the masses of 3C273 and 3C48 can be estimated

as follows: From the line broadening, we can estimate the kinetic velocity of emitting atoms, which is 1500 km/sec. In order that these atoms be bound gravitationally at a distance of 0.6 parsec the center of 3C273 must contain a mass of at least 10^8 $M_\odot$. This is the lower limit for the masses of 3C273 and 3C48.

One can also obtain the mass from energy estimates. To know the total energy radiated, one needs to know the age of quasars. The energy output rate is 3×10^{46} ergs/sec, equivalent to the nuclear energy output from the burning of one solar mass of hydrogen in one day. In 3C273, there is a jet, component A, 150,000 light years away from the other component, component B. It is most likely that the jet was ejected from 3C273. If one accepts this interpretation, then the age of 3C273 must be at least 150,000 years. This gives a value of 10^{59} ergs for the total energy radiated.

But this is not the whole story about the energy content of quasars. The optical emission can be interpreted as due to collisional excitation caused by the thermal motion of ions. From the shape of the radio spectrum (Fig.6) the radio emission is most likely from synchrotron radiation. Thermal radiation with such strong intensity will require a temperature of the order of 10^9 °K and at this temperature its lifetime against neutrino loss is less than a few days. Relativistic electrons moving in a magnetic field can radiate predominantly in the radio region. To date, we do not know of any way of accelerating high energy electrons with high

efficiency, and it seems consistent with known cases (e.g., the Crab Nebula) that about 1 % of energy stored in all high energy particles may be in the form of high energy electrons. Also magnetic fields contain energy. A minimum estimate of the total energy consistent with radio data gives a value of at least 10^{60} ergs.

The presence of a magnetic field is further supported by the discovery of polarization in the optical region. One does not expect a very large polarization, because the plane of polarization of electromagnetic waves will be rotated while passing through a plasma; the rotation angle is different for different frequencies (Faraday rotation). /for a given band width, the polarization decreases as electromagnetic waves pass through a plasma. At a wavelength of 4500 Å, a polarization of (0.45 $\pm$ 0.15) %, based on 12 observations has been obtained by McDonald. The angle of polarization is defined to $\pm 5^{\circ}$. This indicates that there is a small component of synchrotron radiation in the optical region, as well as the presence of magnetic fields.

To summarize the discussion on the observed features of quasars, we conclude that (1) quasars are massive objects with a mass $\gtrsim 10^{8}\odot$, confined to a space of dimension of about one parsec, (2) they are not composed of stars but seem to be coherent masses, (3) their lifetime is at least 10^{5} years, (4) they radiate radio waves strongly but more strongly in the optical region, (5) their surface is composed of very tenuous matter of a particle number density of the order of $10^{7}/cm^{3}$ and (6) their total energy content is larger than the rest energy of $10^{6} \odot$.

Now I shall discuss some theoretical speculations based mostly

on the energy requirement of quasars. All of

the 10^{60} ergs of energy ($= 10^6 \odot c^2$) are in the form of magnetic

fields and high energy particles and a possible energy source is

gravitational energy, which can be released in violent events

(e.g. collapse) and hence all the energy released may be in the

form of high energy particles. The prevalent theory of gravita-

tion is general relativity. General relativity predicts some

singularities of which the Schwarzschild singularity will

be discussed briefly below.

Classically, if one is able to accumulate matter indefinitely

and statically, eventually the escape velocity at the surface will

exceed the light velocity. As an interesting historical sidelight

we remind the reader that in conjunction with the corpuscular theory

of light, Laplace demonstrated in 1795 that a body of the dimension

of the orbit of the earth around the sun, with a density of that of

the earth, would not allow any of its rays to escape. Hence, he

concluded that the most luminous object in the universe may not

be visible.

The same conclusion holds in relativity theory. In fact, the

mass limit calculated according to Newtonian theory is exactly the

same as that predicted in general relativity theory! The light

emitted at a distance R from a sphere of mass M is red shifted by

the factor $\left(1 - \frac{2GM}{Rc^2}\right)^{-\frac{1}{2}}$ as observed by distant observers and for light emitted at the

surface defined by $R^* = 2GM/c^2$, the red shift is infinite. R^* is called the gravitational radius or the Schwarzschild radius. The time dilatation factor is also $\left(1 - \frac{2GM}{Rc^2}\right)^{-\frac{1}{2}}$. To an outside observer, a body falling towards R^* will never reach it, since in approaching it, the time dilatation factor $\left(1 - \frac{2GM}{Rc^2}\right)^{-\frac{1}{2}}$ diverges and the motion will slow down in speed and eventually stop (time machine!). Signals sent out by the falling body will be more and more red-shifted to very long wavelengths. To a local observer falling towards the center, however the time of descent is finite. In fact, from the present radius of the sun $(R_\odot = 7 \times 10^{10}$ cm) the time of descent towards the center, assuming the sun is within its gravitational radius, is less than one day. For a proton, $R^* = 10^{-33}$; for the sun, $R^* = 2.6 \times 10^5$ cm; and for a massive object $M \sim 10^8 \odot$, $R^* \sim 10^{13}$ cm. For a collapsing star in which the pressure can be neglected. In 1939, J.R. Oppenheimer and H. Snyder the of the University of California at Berkeley found that the above conclusion was valid.

Although no light can cross the boundary, gravitational field and electrostatic field (those carried by the so-called longitudinal photons) can be felt by external observers. Thus, Schwarzschild singularity can be detected through its gravitational field but it cannot be seen. Also, because for a co-moving observer the Schwarzschild singularity does not seem to exist, many relativists believe it is just a singularity introduced by the particular coordinate one chooses to describe the gravitational field. Various efforts have been made to find a coordinate system free of Schwarzschild singularity, including a modification of the topology of space-time continuum, but in all cases, singularities always reappear at

other places.

In practice, Schwarzschild singularity sets an ultimate limit on how far a body can collapse gravitationally. This limit is actually approached in the model proposed by F. Hoyle and W. A. Fowler. In a bold attempt, F. Hoyle analysed the conditions for the formation of large coherent masses. The difficulties of forming large masses are: (1) angular momentum, (2) breaking up of large masses to smaller ones prematurely. The period of rotation is proportional to R^{-2} (R is the dimension of the object), but all other time scales (the free fall time, the time of transit of hydromagnetic waves across a body) are proportional to $R^{-3/2}$ in the non-relativistic case. Hence, rotation will prevent matter from condensing further when the speed of rotation at the equator equals the escape velocity. As a comparison, rotation becomes important during the formation of the sun when the radius of the proto-sun is around 10 to 100 times the present value.

In the relativistic region, all time scales have the same dependence on R . Other physical characteristics of the body (density, mass, magnetic field, and so on) then determine which time scale becomes the most important one. In order that a large coherent mass may be formed, gravitational time scale must be the shortest one. A comparison of the gravitatonal time scale $\left(\sim \left(\frac{3\pi}{32G\rho} \right)^{1/2} \right)$ and the hydromagnetic time scale $\left(\sim \frac{R}{H} \left(4\pi\rho \right)^{1/2} \right.$, where H is the magnetic field) shows that, for a magnetic field of 10^{-6} gauss and a

density of 10^{-21} g/cm^3, the gravitational time scale is shorter

than that of the hydromagnetic wave when the mass is greater than

$10^6 \odot$. (As a comparison, the galactic magnetic field is in between

10^{-6} gauss and 10^{-5} gauss, the inter-stellar matter density is

10^{-24} g/cm^3, and the density of nebulae is 10^{-21} g/cm^3). From a

similar comparison of the rotation time scale($\sim \omega^{-1}$) with the gravita-

tional time scale, one finds that for $\omega = 10^{-15}$ sec^{-1} (the angular

velocity of a galaxy), the condition is $\rho > 5 \times 10^{-24}$ g/cm^3. Thus

one need not have a spectacular density in order to overcome the

limit imposed by angular momentum.

In this simple argument, one does not consider the transfer

of angular momentum from one part of the body to the other. If

considerable amounts of angular momentum are transferred, the pre-

vious argument is not valid. It is not known whether angular mo-

mentum may be transmitted in large quantities. Optimistically,

one hopes the inner part can fall a great way before transfer of

angular momentum becomes important.

Thus, conceivably, a large mass ($\gtrsim 10^6 \odot$) can condense to a

density of around 10^{-16} g/cm^3. At this density due to rotation,

[Fig. 9] the body becomes appreciably flattened. Let the thickness of the

disc be W, the diameter be D. Now the time scale for the vertical

direction is determined by W and this gravitational time scale is

much larger than the hydromagnetic time scale. Fragmentation can

now take place in the outer part. The mass m in each fragmented

blob is given by

$$\frac{m}{M} \sim \left(\frac{W}{D}\right)^2$$

for $W/D = 10^{-2}$, $M = 10^6 \odot$, we have $m = 10^2 M\odot$.

The temperature of the gas can be calculated by applying the virial theorem (which equates the thermal energy of a self-gravitating sphere to its self-gravitational energy.) The calculated value for this case is around 10^4 °K, somewhat below the ionization temperature of hydrogen at the corresponding density. Further contraction (now taking place individually in smaller blobs) will raise the temperature, and hence ionize the gas. The ionization of hydrogen requires an energy of about 10^{13} ergs/g and the thermal (and gravitational) energy is about 10^{12} ergs/g at 10^4 °K. The gravitational energy is proportional to R^{-1}. To obtain an energy of 10^{13} ergs/g, a contraction by a factor of ten, or an increase in density by a factor of 10^3 is needed. The density suddenly increases from 10^{-16} g/cm^3 to 10^{-13} g/cm^3.

The gas cloud becomes opaque to radiation only until $\rho \sim 10^{-11}$ g/cm^3. During the contraction phase, energy has to be supplied to the radiation field as well. Hence the contraction cannot stop until a density of 10^{-11} g/cm^3 is reached. As we have mentioned earlier, stars of masses $\gtrsim 10^2 \odot$ are not stable against pulsation. A check in the thermodynamic mechanical properties of the star shows that the star is only marginally in a stable equilibrium. Now a rapid contraction takes place almost like a collapse, suddenly raising

the density from 10^{-16} g/cm^3 to 10^{-11} g/cm^3 in a time comparable to the gravitational free fall time. Will the collapse stop? In a star of a few solar masses, we are quite sure the collapse will stop before nuclear energy generation runs wild. The kinetic energy associated with the collapse will be damped out in the subsequent oscillations. In a $10^2 \odot$ star, the collapse will probably overshoot, and the accompanied oscillation will have very large amplitude.

The most efficient damping mechanism is the electron pair annihilation process of neutrino production. But this is important only when $T > 10^9$ $^\circ$K; at lower temperature, there is no damping. Since the temperature fluctuation of the star is very large, nuclear reactions (hydrogen burning) will proceed in a somewhat erratic manner. An estimate of the actual time scale for nuclear burning is difficult; but, in order to fit those sporadic light variations in 3C273, the time scale for nuclear burning should he around one year. This rate also fits the observed energy flux (3×10^{46} ergs/sec).

S. A. Colgate of Lawrence Radiation Laboratory and A.G.W. Cameron of Goddard Institute for Space Studies pointed out, however, that F. Hoyle's mechanism does not provide enough high energy particles for radio emission. Shock waves generated by supernovae, travelling in the very tenuous matter in which these stars are embedded, will accelerate particles to relativistic velocities. A considerable amount of gravitational energy

will be released during supernova collapse. Moreover, shock waves will generate hydromagnetic waves throughout the medium which may explain the long term light variations (15 year variation) of 3C273.
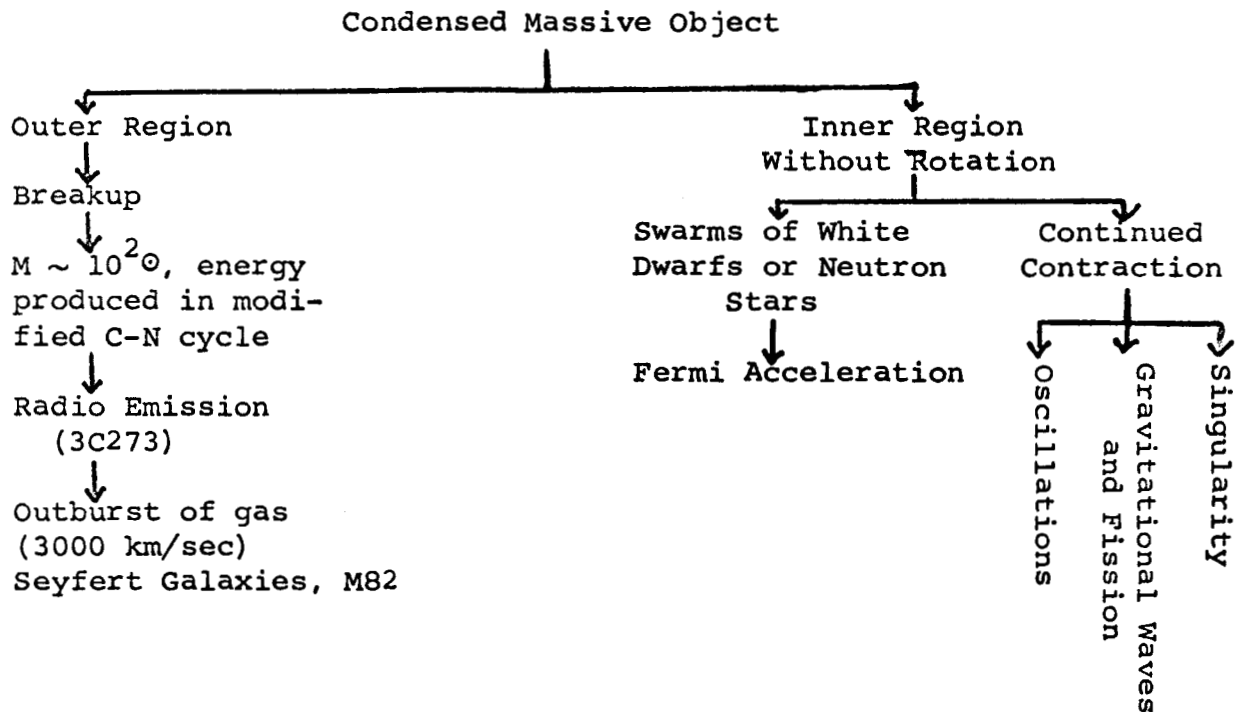
Remnants of these massive stars may be in the form of neutron stars of Schwarzschild singularity. Either neutron stars or Schwarzschild singularity may accelerate particles to relativistic speeds. This may be the mechanism that produced a jet in M87 (a galaxy). This idea of acceleration is due to Ya. B. Zel'dovich of USSR.

Another alternative suggested by F. Hoyle is that the inner region of the big body can collapse gravitationally to extreme density; rotation can either be crushed by gravitational force or dissipated by radiating gravitational waves, assuming a non-cylindrical shape was achieved through fission. F. Dyson of Institute for Advanced Study pointed out that the difficulty associated with a gravitational collapse theory was that it would be over in one day (the local time it takes for a test particle to cross the Schwarzschild singularity of $10^2\odot$). How can one get a collapse which will last for over 10^6 years which is needed in quasars?

T. Gold of Cornell pointed out that in supernova explosions the light output increases rapidly but declines slowly, and this is in contradiction to what is observed. (See Fig. 8).

F. Hoyle summarized his talk by a table which is reproduced below:

Table II

Condensed Massive Object

```
                    Condensed Massive Object
                              |
         +--------------------+--------------------+
         |                                         |
   Outer Region                              Inner Region
         |                                  Without Rotation
   Breakup                                        |
         |                          +-------------+-------------+
   M ~ 10^2⊙, energy                |                           |
   produced in modi-         Swarms of White              Continued
   fied C-N cycle            Dwarfs or Neutron           Contraction
         |                        Stars                        |
   Radio Emission                  |                 +---------+---------+
     (3C273)               Fermi Acceleration        |         |         |
         |                                      Oscillations  Gravitational  Singularity
   Outburst of gas                                            Waves and
   (3000 km/sec)                                              Fission
   Seyfert Galaxies, M82
```

W. A. Fowler then discussed a similar mechanism for massive objects. As condensation takes place, the inner part begins to rotate rapidly, and fission can take place. When the inner part bifurcates into a non-symmetrical form, gravitational radiation will take place radiating away an appreciable amount of rotational energy (which is comparable to the total rest energy). This raises the potential energy outside and part of matter will have a positive binding energy. Mass will be ejected. The difficulty here, as pointed a number of others, is that one cannot avoid a coupling between inside and outside, if fast non-symmetrical rotation takes place.

T. Gold presented the idea that if stars escaping from star clusters can carry away enough angular momentum, star clusters can collapse, and collisions between stars will occur

more frequently. Energy released in such collision processes is fairly large, and certain radio phenomena can be explained.

A number of other topics not related to massive objects, but relevant to gravitational collapse or to galactic structure were also discussed.

E.M. Burbidge reviewed several proposed mechanisms for strong radio sources. Originally a radio source in Cygnus was identified with a pair of galaxies appearing to be in collision. R. Minkowski of University of California at Berkeley postulated that the collision between normal galaxies can generate high energy particles responsible for radio emission. Later this idea was rejected because the energy thus released is far too small. Also the number of radio sources occurring is much greater than what one would expect from the frequency of galactic collisions for most optically identified sources not asso- ciated with clusters of galaxies. G. R. Burbidge of the University of California at La Jolla and F. Hoyle proposed that collisions between galaxies and anti-galaxies (com- posed of anti-matter) might give enough energy. However, there are many inconsistencies in this proposal. For example, why should matter and anti-matter be separated until the right moment to anni- hilate? Another mechanism is the emission of radio waves through the interaction of turbulent magnetic field with gases. One can perhaps explain the radio emission from M82 by this mechanism, but in an elliptical galaxy, there is practically no gas! The exis- tence of large scale, strong magnetic fields in elliptical galaxies

is also unlikely.

If one accepts supernova remnants as the only radio emitters in a galaxy, one needs a total number of 10^8 supernova spreading over 10^6 years. I. Shklowsky of U. S. S. R. suggested that during the early stages of galactic evolution, rapid star formation can take place, and supernova activities may be stronger than at present. A.G. W. Cameron modified I. Shklowsky's idea and postulated that in regions rich in gas and low in magnetic field, massive stars can condense simultaneously. After going through their normal evolutionary sequence, they become supernovæ - all occuring in around 10^6 years. Remnants of these supernovae can account for the radio emission. The difficulty is the same as in the proposal of G.R. Burbidge and F. Hoyle: In elliptical radio galaxies there appears to be very little gas.

G. R. Burbidge postulated that in the center of a galaxy, if the separation between pre-supernova stars is around a few light days, the supernova explosion of one of them may trigger the rest of them to become supernova. In order that his mechanism may work, a stellar density of 10^7 stars/cubic parsec is needed. Such a high density may exist and escape detection. However, one does not know of any trigger mechanism.

The suggestion of F. Hoyle and W.A. Fowler that radio sources are due to stars of mass $\sim 10^{6-8} \odot$ also has difficulties which have been pointed out by F. Dyson.

H.-Y. Chiu of Goddard Institute for Space Studies reported on the evolution of pre-supernova

stars. He found a very dense core will develop before a star under-
goes collapse. Almost all the energy released during collapse
will be dissipated in the form of neutrinos. The dense core will
become neutron matter. It is not known if the remains will be
observable. If it is observable, it will be in the X-ray band
(3 - 10 $\overset{o}{A}$ range) for around 1000 years after formations.

E. E. Salpeter reviewed the equilibrium configuration of
neutron stars. At a density greater than 10^{12} g/cm^3, matter is
composed predominantly of neutrons and at an even higher density
(> 10^{16} g/cm^3) hyperons may exist. These neutrons cannot decay
because all eleotron states are filled up. There exists a mass
limit for neutron stars and no static equilibrium configuration
is possible if the mass exceeds this limit. This limit for a per-
fect Fermi gas is $0.76^{\odot}$ (Oppenheimer-Volkoff mass limit). If
real gases are considered, the limit varies somewhat, but
in no case does it exceed $3^{\odot}$.
                                    (London)
H. Bondi of King's College (reported by E.E. Salpeter) derived
a rigorous upper limit for the red shift of light emitted from the
surface of neutron stars, and the limit is $\Delta\lambda/\lambda < 0.615$. A more
realistic limit is found to be around 0.3. (Incidentally, this
also excludes the possibility that the large red shift (> 0.3) of
some quasars is gravitational red shift.) In principle, this is the
upper limit of red shift for light emitted from any self-gravitating
body.

J.A.Wheeler of Princeton discussed another kind of gravitational singularity. He assumed that one can accumulate matter statically until at the center, the time metic g_{oo} vanishes (this corresponds to a classical situation in which the gravitational potential at the center of the body is equal to its rest energy). Any matter dropped through a hole to the center will give away energy equivalent to its rest energy and hence, the total gravitational mass (as observed by external observers through its gravitating effect) cannot increase. Thus, such singularity acts as a gravitational machine, converting all matter into energy. Since the number of nucleons is conserved, J. A. Wheeler postulated the existence of a class of new massless bosons, the δ-ray, which carries the nucleon number. One of the chairmen remarked that δ-rays, if they exist, may be used to transport ponderable matter at light speed (matter transmitter).

However, it is not known if one can really accumulate matter statically until this kind of gravitational singularity comes into existence. All neutron star models studied so far indicate that a dynamical collapse will take place when the mass exceeds the critical mass limit (the mass limit was reviewed by E. E. Salpeter).

A vivid discussion then took place, re-emphasizing some of the points discussed during the meeting. E.L. Schucking of the Southwest Center for Advanced Studies pointed out that other discussions relevant to massive objects, cosmic rays, cosmic X- and Y- rays had

been omitted from the discussion. P. Bergmann of Yeshiva University remarked that/general relativistic effects have been observed only
in the past

in the weak field limit. Now new developments of astrophysics

have made relativity theory a more physical theory. He expressed

hope that a quantized version of relativity theory may play an

important part in understanding massive objects. R. Minkowski

expressed satisfaction that within the past ten

years the technique of optically identifying radio sources had made

great progress. On the other hand there is lacking a theoretical

understanding of the structure of large masses. In one context

J. R. Oppenheimer, Director of the Institute for Advanced/ who pio-
Study,

neered the study of neutron stars and gravitational collapse, re-

marked that the present situation in interpreting quasars resembled

that of quantum electrodynamics 18 years ago when all one had was

confusion and lots of data. If the meeting taught us anything, it

has taught us that those two dark clouds in the otherwise clear

sky of physics, which Kelvin described at the turn of the last cen-

tury (at that time he meant natural radioactivity and x-rays) are
very
still here. But they are now to be found at the edge of our
^

universe.

Acknowledgement

References

The following is a list of references with which the author is acquainted.   He does not claim that this list is representative or complete.

Radio Spectra

1. R.G. Conway, K.I. Kellermann, and R.J. Long, "The Radio Frequency Spectra of Discrete Radio Sources," Monthly Notices of the Royal Astronomy Society 124, 343 (1962).

2. R. C. Roeder and G.C. McVittie, "The Luminosity Function of Extragalactic Radio Sources," Astrophys. J. 138, 299 (1963).

3. T.A. Matthews and A.R. Sandage, "Optical Identification of 3C48, 3C196, and 3C286 with Stellar Objects," Astrophys. J. 138, 30 (1963).

4. M. Ryle .and A.R. Sandage, "The Optical Identification of Three New Radio Interferometer Observations-Objects of the 3C48 Class," Astrophys. J. 139, 419 (1964).

5. L.R. Allen, R. H. Brown, and H.P. Palmer, "Analysis of the Angular Sizes of Radio Sources," Monthly Notices of the Royal Astronomy Society 125, 57 (1962).

Lunar Occultation Observations

6. C. Hazard, M.B. Mackey, and A.J. Shimmins, "Investigation of the Radio Source 3C273 by the Method of Lunar Occultation," Nature 197, 1037 (1963).

7. C. Hazard, "The Method of Lunar Occultations and Its Application to a Survey of the Radio Source 3C212," Monthly Notice of the Royal Astronomy   Society 124, 27 (1962).

Light Variation of 3C273

8. H.J. Smith and D. Hoffleit, "Light Variations in the Superluminous Radio Galaxy 3C273," Nature 197, 650 (1963).

9. A.R. Sandage, "Intensity Variations of 3C48, 3C196, and 3C273 in Optical Wavelengths," Astrophys. J. 139, 416 (164).

Red Shift Interpretations

10. M. Schmidt, "A Star-like Object with Large Red Shift," Nature 197, 1040 (1963).

11. J.B. Oke, "Absolute Energy Distribution in the Optical Spectrum of 3C273," Nature 197, 1040 (1963). (Hα line was found in the infrared spectrum.)

12. J.L. Greenstein and T.A. Matthews, "Red-Shift of the Unusual Radio Source 3C48," Nature 197, 1041 (1963).

13. J. L. Greenstein, "Quasi-Stellar Radio Sources," Sci. Amer. 209, 54 (1963).

Figure Captions

Figure 1.

Absolute radiomagnitudes and absolute photographic magnitudes of
galaxies and quasars are plotted here. The absolute photographic
magnitude is a measure of the optical power and has been defined
previously in a footnote. The absolute radio magnitude M_r is
defined to be

$$M_r = - 54.1 - 2.5 \log_{10}S$$

where S is the radio power in watts per second per cycle band-
width at 400 megacycles per second (M_c/sec), with the exception of
a few normal galaxies where S is evaluated at 100 M_c/sec. δ is the
ratio of radio power to optical power normalized to unity for
normal galaxies. Other radio galaxies have a value of δ up to 10^4.
3C273 and 3C48 are found in a region in the graph where no
galaxies are found. The distance of two other quasars 3C286 and
3C196 have not been determined and their possible position in this
graph are indicated by the dotted lines. The sources of data used
here are references (1) and (2).

Figure 2.

Actual photograph of 3C48 and an enlarged image of 3C48. D and B
are reference stars from which the magnitude of 3C48 is dtermined.
A faint nebulosity can be vaguely seen. (Photo taken by T.A.
Mathews and Alan R. Sandage, with the Hale Telescope at Mt. Wilson
ref. (3)).

Figure 3.

The intensity observed as a function of time in lunar occultation.
Figure (a) shows the diffraction pattern calculated for a point
source, (b) shows that of an extended object. Note the decrease in
the amplitude for an extended object. The angular diameter ω is
related to β by

$$\omega = \beta / (\lambda/2d)^{\frac{1}{2}}$$

where λ is the wave length and d is the distance to the moon. v is
proportional to the time. v = 0 corresponds to the geometrical
shadow. I_0 is the relative flux density at the edge of the geo-
metical shadow. (c) is an actual emersion diffraction pattern of
3C273 at 410 mc/s on Aug.5,1962. Note the similarity to that for a
source (a). (d) is an actual immersion diffraction pattern of Oct.26, point
1962, at 1420 mc/s. Note the resolution of 3C273 into a point
source and an extended source. (Ref. 6,7).

Figure 4.

Diagram of the radio source 3C273. The sides of the full triangles represent the position of the limit of the moon at the time of occultation. The broken lines represent the widths of the equivalent strip source as measured at 410 mc/s for each of three position angles indicated.(Ref. 6)

Figure 5.

Actual photograph of 3C273. Note the jet which points to the star-like object. Although at a distance of 1.8×10^9 years, the star-like object is easily seen through an amateur's 6" telescope.(Photo taken by A.R. Sandage with the Hale telescope at Mt. Wilson.)

Figure 6.

Radio spectrum of 3C273. The black dots are measurements of both components. The squares give the spectrum of component A; the open circles of component B. The line through the open circle shows how one could fit a thermal spectrum to it. But this interpretation seems highly unrealistic. (Courtesy of W. Priester)

Figure 7.

Schematic spectra of 3C273, 3C48, and 3C47 together with Cyg A and 3C295. The ordinate is the redshift $\Delta\lambda/\lambda$. Forbidden lines are represented by black dots. The numbers underneath the dots indi-cate the relative strength of the lines (number 1 being the strongest line in the spectrum.) (Courtesy of W. Priester)

Figure 8.

Light variation curve of 3C273 as analysed by H. J. Smith and D. Hoffleit from old sky patrol plates. These data represent statistical average over a few days of observations and the standard deviation is as indicated by vertical line segments, H. J. Smith pointed out that a big light crash of 3C273 occurred towards the end of Oct., 1929.

Figure 9.
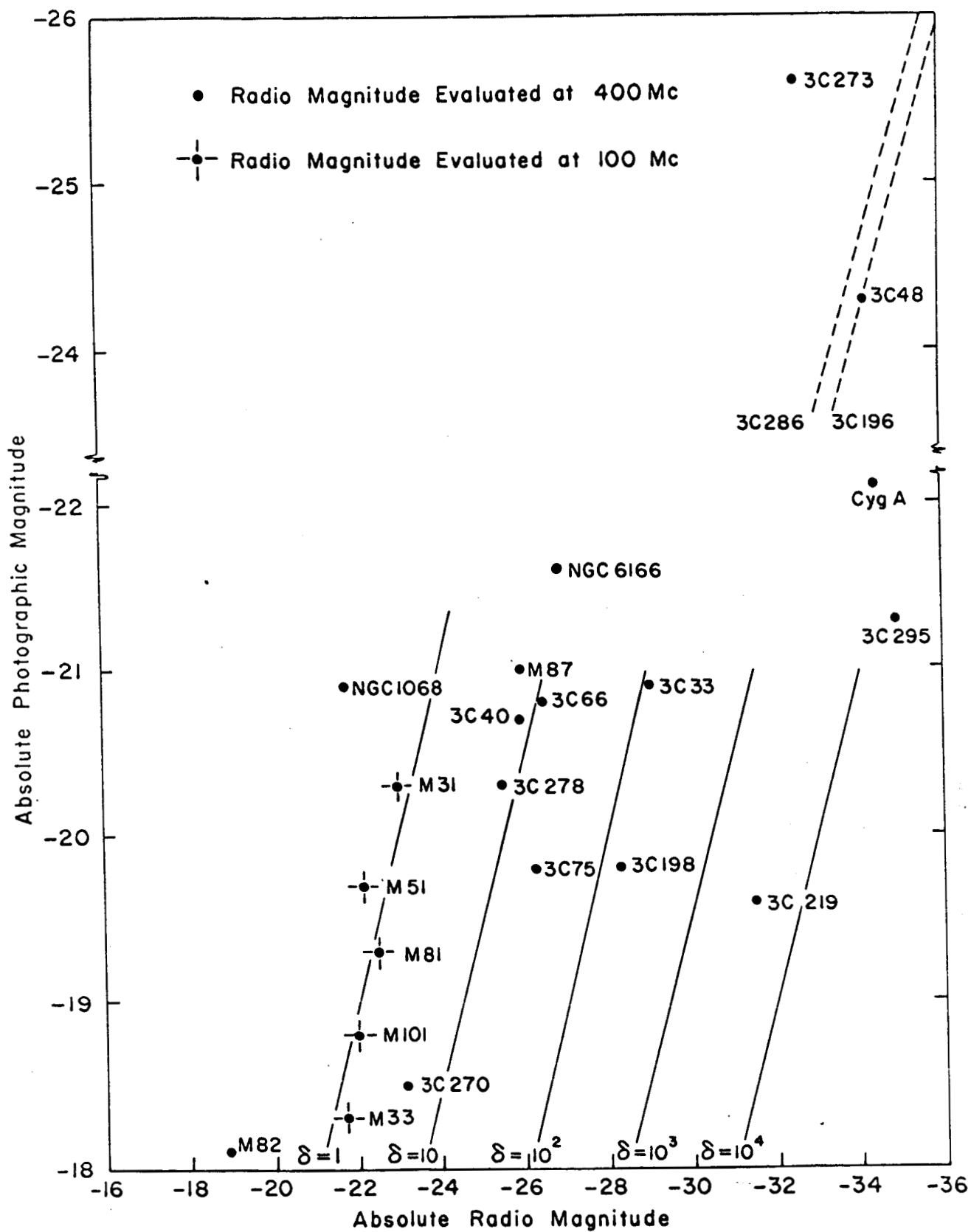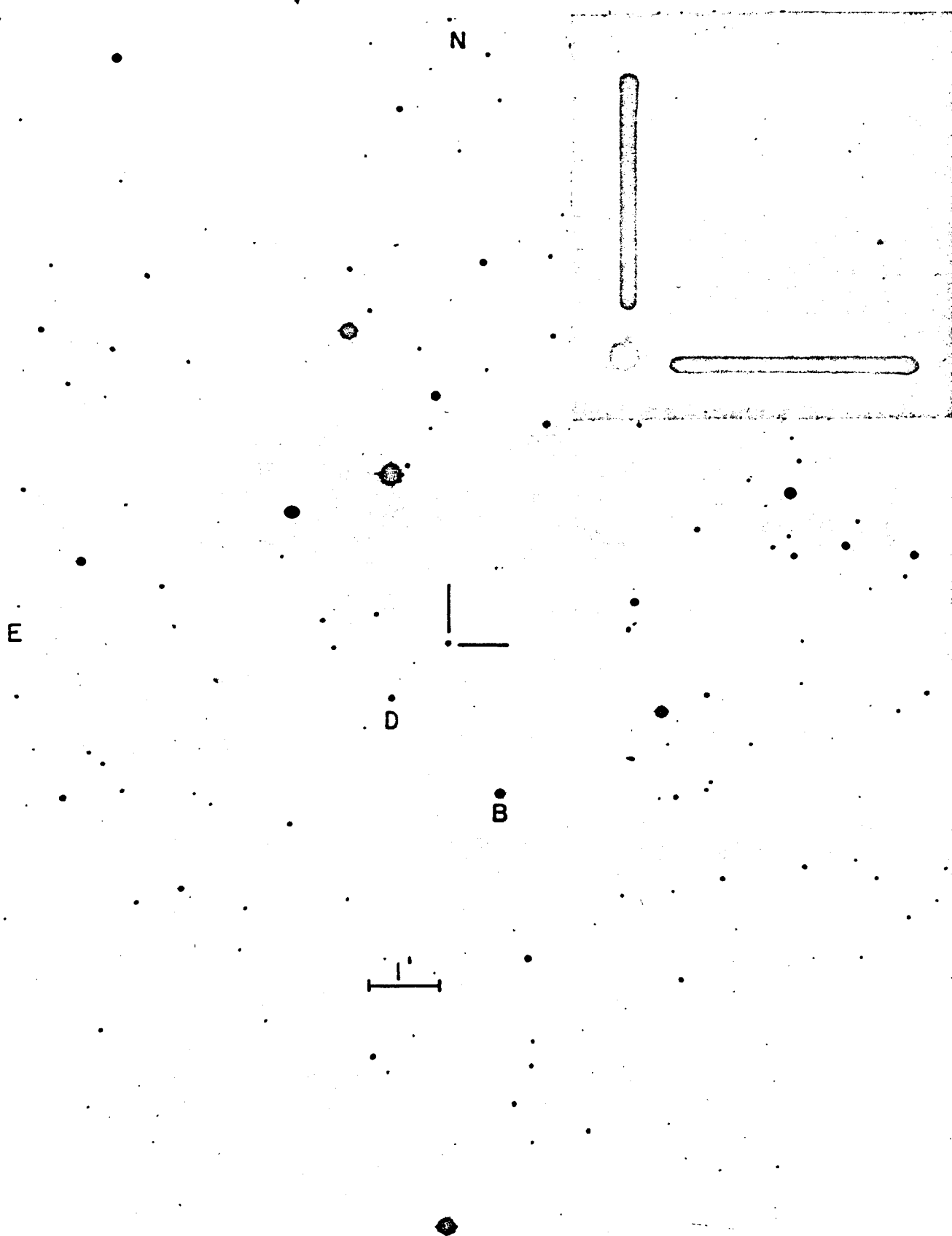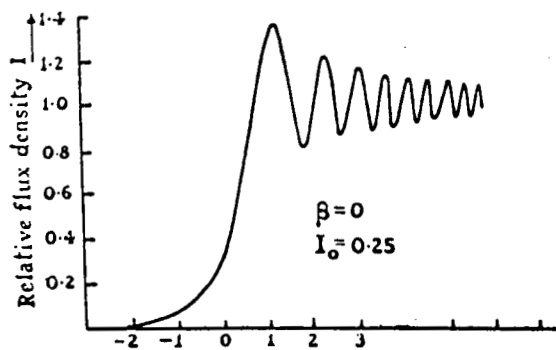
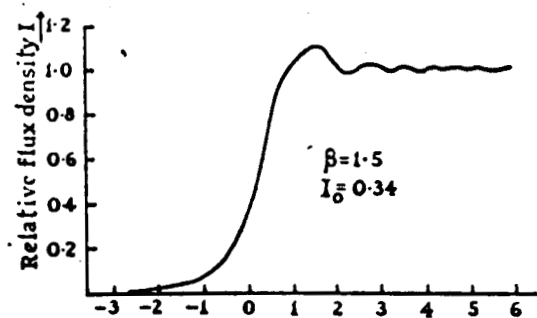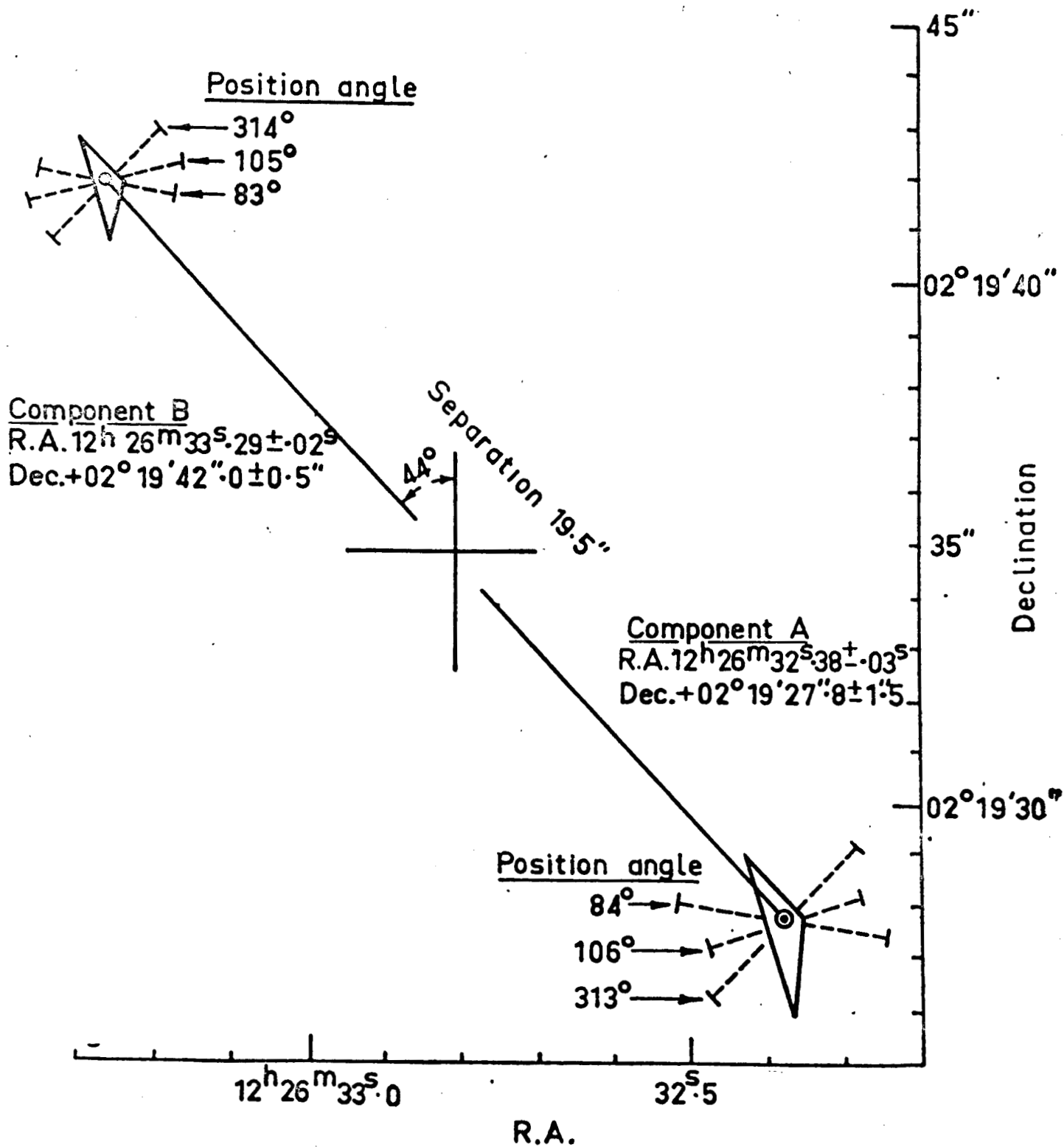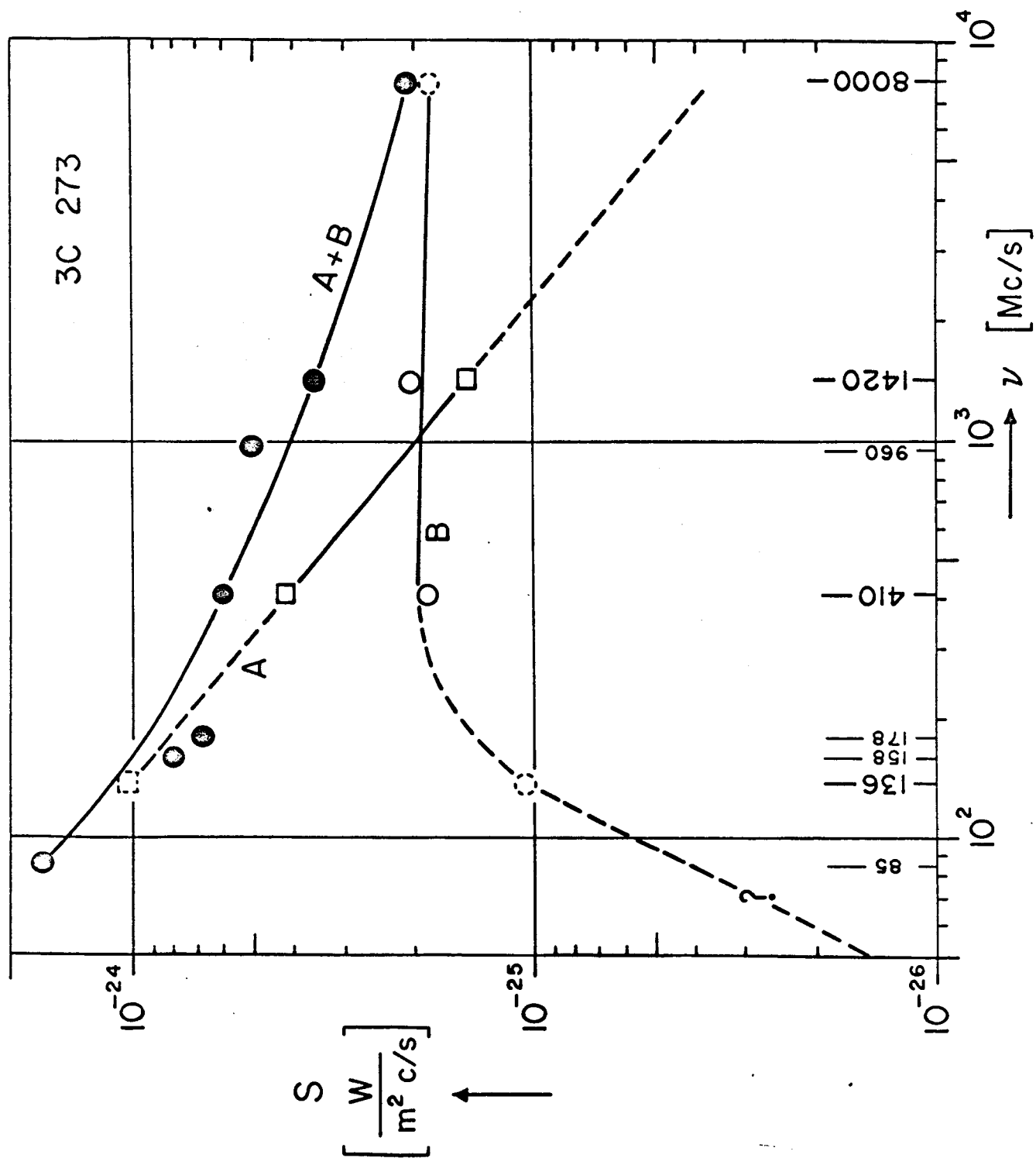Flattened disc in Hoyle's theory.

Figure 1.

Figure 2.
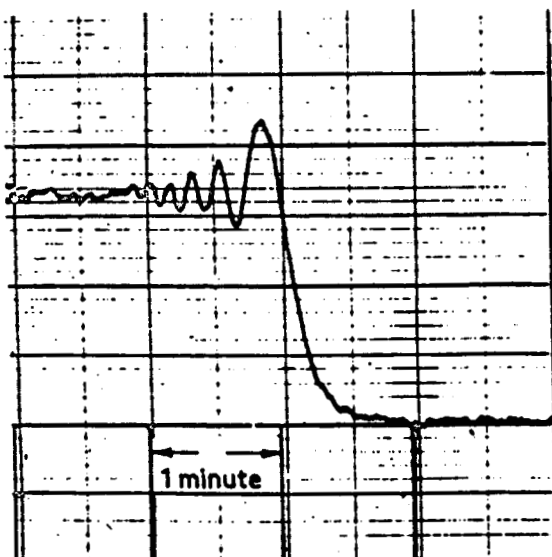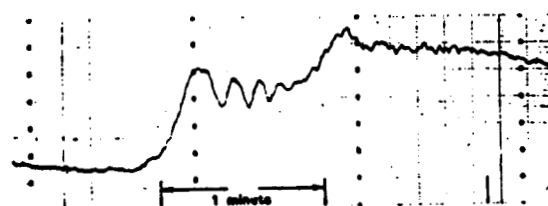
Figure 3.

Figure 4.

Figure 6.

RADIO SOURCE 3C 273

PHOTOGRAPHIC MAGNITUDE

Figure 8.

Sub Condensation Mass M

Disk Thickness

W

D

Figure 9.